Influence of hydraulic loading rate, simulated storm events and seasonality on the treatment performance of an experimental three-stage hybrid constructed wetland system

Cristina Ávila, Joan García and Marianna Garfí

GEMMA - Environmental Engineering and Microbiology Research Group, Department of Civil and Environmental Engineering, Universitat Politècnica de Catalunya-BarcelonaTech, c/ Jordi Girona, 1-3, Building D1, E-08034, Barcelona, Spain

*Corresponding author: Marianna Garfí
Tel: +34 934016412
Fax: +34 93 4017357
Email: marianna.garfi@upc.edu

Abstract

An experimental hybrid system based on an anaerobic reactor followed by three stages of different constructed wetland configurations was evaluated when operating under a high hydraulic loading rate (HLR = 0.27 m d^{-1}, considering the area of the VF beds) for one year, which corresponds to four times the nominal hydraulic loading rate, with the purpose of reducing the specific area required. Moreover, in order to assess its buffer capacity, a major storm event was simulated by increasing the HLR 10 times during 1 hour. A tracer experiment was also performed to determine the experimental hydraulic retention time (HRT). The system consisted of a hydrolytic upflow sludge blanket (HUSB) reactor followed by two alternating 1.5 m^2 vertical subsurface flow, a 2 m^2 horizontal subsurface flow and a free water surface constructed wetlands operating in series. The system achieved very high values of removal of solids, organic matter and nutrients (82, 93, 96 and 75% for COD, BOD_5, TSS and NH_4-N, respectively). Removal of PO_4-P and SO_4^{2-} were though fairly low, of 11 and 10%, respectively. There was a seasonal effect in the system for parameters whose removal highly depends on biodegradation, being enhanced under warmer conditions (98 and 92% removal of BOD_5 and NH_4-N in summer vs. 87 and 67% removal of BOD_5 and NH_4-N in winter). The experimental HRT of the entire system was of about 38 hours, which greater than the theoretical HRT (28 h). During the simulation of the storm event removal efficiencies did not vary significantly from the ones obtained under normal conditions (average of 83, 99 and 80% for COD, TSS and NH_4-N removal, respectively). The system showed a very good buffer capacity coping with sharp fluctuations in flow to be treated, showing to be an adequate solution for wastewater treatment in small communities. The specific area requirement under the long-term operation showed to be as low as 2 m^2/PE.

Keywords

Decentralized; ecotechnology; green infrastructure; heavy rainfall; hybrid treatment wetland; urban wastewater.

1. Introduction

In recent years there has been a substantial progress in the implementation of wastewater treatment systems around the world. The sanitation model generally practiced consists of the development of extensive collection systems directing wastewater into a centralized treatment plant. This has a very high cost and requires a high energy demand, including procedures which are often highly complex. Although in large urban areas of industrialized countries the lack of space and the high flow make the use of conventional systems irreplaceable, at small-scale a paradigm shift is necessary, in which a decentralized approach has to predominate. This requires finding alternative technologies that present great versatility and adaptability, good integration in the natural environment, and costs of implementation and operation well below those produced in the conventional treatment of urban wastewater.

In this sense constructed wetlands (CWs) represent a tool to facilitate the transition to this new model. The infrastructure needed for its construction is very simple and affordable, and operation and maintenance are relatively easy and inexpensive. They have low or no energy consumption, low sludge production, and do not require the addition of chemical reagents. In addition, these systems provide habitat for wildlife and in consequence increase biodiversity, thus they can be implemented to restore degraded areas. They are also resilient to large fluctuations in water quality and flow, as well as air temperature (Ávila et al., 2013c). Considering these treatment systems are based on the knowledge of the functioning of natural systems, it is a very appropriate technology for its application in developing countries since they do not generate technological dependence (García et al., 2010; Kadlec and Wallace, 2009). What is more, wetlands can be constructed using local materials and labor, which is also a great attribute to these countries.

There are different wetland types depending on the flow type, which can be divided into subsurface flow (which include vertical and horizontal subsurface flow wetlands, depending on the direction of the flow) and surface flow (which has a free water table on top of a soil). Each wetland type is especially good at promoting specific mechanisms due to the different physico-chemical characteristics taking place within each configuration. Indeed, wetlands can be combined in series constituting hybrid systems where advantages and disadvantages of each wetland type can balance each other out (Vymazal, 2013). There exist various hybrid CW systems in the world, both at experimental (Ávila et al., 2013a, 2014b; Herrera-Melián et al., 2010; Tunçsiper, 2009;) and at full-scale (Ávila et al., 2013c, 2014a; Ayaz et al., 2012, 2015; Masi and Martinuzzi, 2007; Öövel et al., 2007), showing to be highly effective in removing a wide range of contaminants, including recalcitrant substances, and oftentimes producing a final effluent which can be reused.

The removal of contaminants in CWs occurs as a result of complex physico-chemical and microbial interactions. The rates of these processes depend on a variety of design and operational factors, as well as environmental conditions and inflowing wastewater quality (Ávila et al., 2013b, 2014c; Button et al., 2014; Paing et al., 2015). These include parameters such as type of primary treatment, depth of the bed, hydraulic loading rate or feeding strategy, among others. One of the key parameters is the type of primary treatment, whose implementation before constructed wetlands is strongly recommendable in order to reduce solids loading applied to the wetland, which may cause clogging and reduce the lifespan of the system (Pedescoll, et al., 2011a). This typically consists of settlers, septic or Imhoff tanks (Puigagut et al., 2007), mainly physical treatments, which have a removal efficiency of ca. 30-40% for biochemical oxygen demand (BOD) and ca. 50-60% for suspended solids (Tchobanoglous and Burton, 1991). Recently, anaerobic reactors have been used as primary treatment. The upflow anaerobic sludge blanket (UASB) and hydrolytic upflow sludge blanket (HUSB) reactors are good alternatives to conventional primary treatment since they are able to produce effluents with fairly lower concentrations of organic matter and suspended solids (up to 80% removal) (Álvarez et al., 2008; Barros et al., 2008; Diaz et al., 2008; Dornelas et al., 2009). In a HUSB reactor the water circulates upwardly through a sludge bed maintained under anaerobic conditions. These are essentially UASB reactors operated at a lower hydraulic retention time (HRT) (from 2 to 7 h) in order to avoid methanogenesis as much as possible, but instead promoting the hydrolysis of organic matter, thus helping preventing or delaying clogging processes. In general, solids retention time in HUSB reactors is maintained for over 15 days in order to achieve high hydrolysis rates (Pedescoll et al., 2011a, b; Ruiz et al., 2008).

However, depending on design, constructed wetlands usually require a larger land area than conventional treatments. In fact, the specific area needed for CWs system was estimated to be around 5-6 (Kadlec and Wallace, 2009) and 2-3 (Molle et al., 2004) m^2/PE for HF and VF CWs, respectively, which is much higher than that required by conventional wastewater treatment technology (much less than 1 m^2/PE) (Veenstra et al., 1997). Moreover, the presence of major storm events could hinder the correct functioning of these systems, especially in tropical and subtropical areas where there is a predominant rainy season. Indeed, only few studies assessed the robustness of constructed wetlands during heavy rainfall events (Ávila et al., 2013c).

An experimental three-stage hybrid constructed wetland system was previously monitored while operating at a design hydraulic loading rate (HLR) of 0.06 m d^{-1} and also under punctual HLRs of 0.13 and 0.18 m d^{-1} (taking into consideration only the area of VF beds, i.e. 3 m^2) (Ávila et al., 2013a, 2014b). The results suggested that the system could be capable of handling much larger loads, and therefore the main goal of this study was to evaluate the treatment performance of the hybrid CW system when operating under a very large HLR (0.27 m d^{-1}) in order to reduce the specific area required. For that purpose, the system was monitored during one year, and the seasonal influence was evaluated. Additionally, in the present study a major storm event was simulated and its impact on treatment capacity was assessed. What is more, in order to estimate the hydraulic retention time a tracer experiment was conducted. Finally, this treatment plant was previously operated with an Imhoff tank as a primary treatment, but replaced by a HUSB reactor during this study period, so as to test whether it had a higher retention of solids.

2. Materials and methods

2.1. Description of the treatment system

The research was conducted in a treatment system which was set outdoors at the experimental facility of the GEMMA research group (Department of Civil and

Environmental Engineering of the Universitat Politècnica de Catalunya-BarcelonaTech, Spain). This experimental plant consisted of a stirred storage wastewater tank, originally followed by an Imhoff tank but replaced by the time of this study by a HUSB reactor. This was followed by two VF CWs working in parallel, one HF wetland and, finally, one FWS wetland in series (Fig. 1). The system started operation in May 2010.

During the period considered in this study (April 2013 – May 2014) the treatment plant operated at a constant input flow of approximately 800 L d^{-1} (HLR = 0.27 m d^{-1}), which corresponds to 4 times the original design flow of 200 L d^{-1} (Ávila et al., 2013a). The implemented value of HLR falls within the range of the highest values ever applied to VF wetlands reported in the literature, such as the 0.25 m d^{-1} at Platzer (1999), the 0.295 m d^{-1} implemented at Vymazal and Kröpfelova (2011), or the value up to 1.37 m d^{-1} reported at Arias et al. (2003).

Urban wastewater from a nearby municipal sewer was daily pumped into a raw wastewater tank before it flowed into a HUSB reactor (0.25 m^3), which had an internal diameter of 0.44 m and a useful height of 1.7 m. The nominal HRT was of 7.5 hours (for a flow of 800 L d^{-1}). This reactor was equipped with 8 taps, positioned vertically in series, starting at a height of 40 cm and each one located at a distance of 20 cm from each other. This distribution made possible the regulation of the level of the sludge bed inside the reactor by opening the taps and discharging a part of the sludge layer. In order to accelerate the correct operation of the HUSB reactor and the stabilization of the sludge layer, it was inoculated with secondary sludge from a full scale wastewater treatment plant (Gavà, Catalonia, Spain). In particular, 50 L of sludge were inoculated in order to achieve a desired concentration of volatile suspended solids (VSS) of 10 g/L, so as to ensure a proper operation. Effluent of the HUSB reactor flowed by gravity from tap 8 into a storage tank (0.2 m^3) and from this point water was conveyed into two parallel 1.5 m^2 VF beds alternating their operation in cycles of feed and rest (3.5 days each). These were intermittently fed by means of hydraulic pulses with a flow of around 30 L per pulse, resulting in about a pulse per hour. Effluent of VF beds was sent to a 2 m^2 HF wetland, and finally pumped into a 2 m^2 FWS wetland. Feeding of the HF and FWS units was done in a continuous mode by means of peristaltic pumps. All wetland units were constructed in polyethylene and were planted with *Phragmites australis* since the commissioning period, thus the vegetation was very well established during the time of the study. For specific design and operational parameters of the system the reader is referred to Table 1 and to further references (Ávila et al., 2013a, 2014b).

2.2. Tracer test

By evaluating the movement of an inert substance (i.e. potassium bromide) through the treatment units a residence time distribution can be determined. With the purpose of having a better understanding of the hydraulic behavior of the hybrid system and estimate its experimental HRT, a continuous hydraulic tracer test was carried out in the treatment plant. The total theoretical HRT in the CW units (without the HUSB reactor) was of a minimum of 21 h, taking into account the HF and FWS units, since the HRT in VF beds is not possible to be predicted and is expected to be of hours.

The tracer solution was prepared in a deposit by adding 4 g of potassium bromide (KBr) to 20 L of water, and it was mixed thoroughly so that the tracer salt was completely dissolved. This mixture was homogenized and injected into the stirred storage tank distributing the primary effluent (HUSB effluent) into the VF wetlands, by means of a peristaltic pump obtained from Damova (Barcelona, Spain). This was synchronized to the peristaltic pump feeding wastewater into the system, so as to reach a homogenized final bromide concentration in wastewater of about 12 mg L^{-1}. In order to ensure the desired concentration from the beginning, this storage tank was emptied before the test started.

The tracer test started when the storage tank where the tracer was injected was filled up with HUSB effluent. To achieve a good tracer curve, tracer test was carried out continuously during 36 hours. Sampling details are explained in Section 2.4.

2.3. Simulation of a major storm

At the end of the monitoring period under normal conditions, a major storm, a characteristic phenomenon of tropical areas, was simulated in the treatment plant. The aim was to assess the appropriateness of the system for tropical climate regions, given by its robustness and buffer capacity to hydraulic overloads. Note that the first-flush event which typically follows a storm event after a dry period caused by the dragging of solids from sewerage system was not reproduced in this experiment, and instead just the hydraulic loading rate was increased.

The heavy rainfall was simulated by increasing the inflow 10 times during 1h, through mixing the usual wastewater flow with tap water. The treatment plant had to be adapted accordingly, and the two peristaltic pumps that feed the HF and the FWS were changed by two centrifugal pumps (Damova, Barcelona, Spain) in order to meet the new input flow. During this simulation the pilot plant worked under an inflow of 333 L h^{-1} (33 L of wastewater + 300 L of drinking water) during 1 h. The duration of the experiment was 10 hours. Sampling details are explained in Section 2.4.

2.4. Sampling strategy and analytical methods

Monitoring of the treatment plant performance under normal conditions (HLR = 0.27 m d^{-1}) took place from April 2013 to May 2014. Grab samples were caught on a weekly basis on the same day of the week (Tuesdays at about 10 am) by taking about 1.5 L of sample at the effluent of the different treatment units (Fig. 1). Measurement of onsite water quality parameters (i.e. pH and redox potential –E_H-) was done at the time of sample collection, and samples were taken to the adjacent laboratory for the analysis of the following parameters: total suspended solids (TSS), chemical oxygen demand (COD), biological oxygen demand (BOD_5), ammonium nitrogen (NH_4-N), nitrate and nitrite nitrogen (NO_x-N), orthophosphate phosphorus (PO_4-P) and sulfate (SO_4^{2-}). The influence of season on the treatment efficiency of the system was evaluated by dividing the one-year dataset into four periods: spring (Mar-June; average air T = 14ºC), summer (June-Aug; average air T = 23ºC), fall (Sep-Dec; average air T = 16ºC) and winter (Dec-Mar; average air T = 8ºC).

The sludge blanket within the HUSB reactor was sampled twice a week to ensure that VSS concentration was lower than 10 g/L. If the concentration of volatile solids was far below theoretical values, the following sludge blanket sample was taken after three weeks, in order to let solids concentration increase. On the other hand, if the concentration exceeded the theoretical value, another sample was taken the following week and a purge was done. Samples to measure solids within the HUSB reactor were taken from taps 1 to 4, 6 and 8.

For the evaluation of the major storm event, samples were taken at the effluent of each treatment unit. The first sample was taken just before the beginning of the storm (t=0) and immediately after (t=1) and then samples were taken hourly during 9 hours. These samples were analyzed for organic matter (BOD_5, COD), TSS and NH_4-N. Onsite measurements of pH and E_H were also taken at the time of sample collection.

During the tracer experiment, grab samples were taken hourly from the final effluent of the treatment plant from the beginning of the injection, by using an automatic sampler. In order to control if the injected bromide concentration was the desired one, several samples were taken from the storage tank containing the mixture.

Onsite measurements of pH were taken by using a Crison pH-meter. E_H was also measured onsite by using a Thermo Orion 3 Star redox meter. E_H values were corrected for the potential of the hydrogen electrode. The determination of conventional wastewater quality parameters, including TSS, NH_4-N and COD was done by following the Standard Methods (APHA, 2001). BOD_5 was measured by using a WTW® OxiTop® BOD Measuring System. NO_x-N, PO_4-P, SO_4^{2-} and bromide were analyzed using a DIONEX ICS-1000 chromatography system.

3. Results and discussion

3.1. Tracer test

This section show the results achieved from the continuous tracer test executed on the treatment plant on April 28th 2014. In Fig. 2 the obtained tracer test curve is shown. Measured initial concentration of bromide was on average 11.4 mg L^{-1}.

In a continuous tracer experiment the experimental hydraulic retention time corresponds to the time when the asymptote is reached and the concentration remains constant. The tracer curve shows how the initial bromide concentration reached the final effluent after about 31-32 hours of operation. It can be noticed that expected theoretical asymptotic curve was not achieved; instead this curve had many fluctuations/interferences. This can be explained due to the complexity of the system. The treatment plant had three different constructed wetland types, and each one had different hydraulic behavior; moreover intermediate tanks caused temporary retention of the water; however the tracer was only measured at the final effluent. Moreover further interferences are expected from the mode of operation of VF wetlands, fed intermittently, which is expected to cause slight deflections in the curve (Schwager and Boller, 1997). The crucial point is to reach the asymptote.

The tracer test is an indicator of the actual hydraulic retention time of the plant, from the distribution tank before the VF wetlands to the outlet of treatment plant. In this way, results show that wastewater takes about 31 hours to flow through VF, HF and FWS wetlands. Considering the HRT of the HUSB (7.5 h), it can be stated that the experimental HRT of the treatment plant is about 38 h, which is greater than the theoretical HRT (28 h).

3.2. General performance of the hybrid treatment system

This section exposes the performance of the hybrid treatment system while it was operated for a year under a flow of 800 L/d (HLR = 0.27 m d^{-1}). Results are shown in Table 2.

As previously observed, E_H values in the raw wastewater (+95.6 ± 82.7 mV) were high in our experiment due to prolonged stirring of the water in the influent wastewater tank, which was unavoidable (Ávila et.al, 2013a). As expected, these values slightly declined as the wastewater passed through the HUSB reactor (-105 ± 36 mV) where anaerobic conditions prevailed. Water was again oxidized within the VF beds due to its characteristics. Average E_H values in the final effluent were of +105 ± 59 mV.

Average organic loading rate (OLR) during this period was 103 g BOD_5 m^{-2} d^{-1} (considering the surface area of the VF beds –i.e. 3 m^2-), which is a very high value for this type of systems. It is to be mentioned that the neighborhood's wastewater studied is residential and holds high water consumption in comparison to other areas of Barcelona. Moreover, there is a high presence of schools in the area. For this reason influent characteristics are very variable. Average influent COD and BOD_5 concentrations were almost double of those found at the experiment operating under the nominal HLR (Ávila et al., 2013a).

Average total removal efficiencies for the entire system were generally high, with values of 82 ± 9% for COD and 93 ± 6% for BOD_5. Note that removal efficiencies would be even greater if the effect of evapotranspiration had been taken into account and removal rates calculated in mass. It can be observed that the majority of organic matter removal occurred mostly in the VF beds, where removal efficiencies were of 56% for COD and 85% for BOD_5. Moderate removal happened in the HF (53%) and FWS (22%) wetlands. These values were similar to those found by Ayaz et al. (2015) in a hybrid mesocosm of similar configuration consisting of a UASB reactor followed by a 18-m^2 HF and a 13-m^2 VF in series, where the elimination of organic matter was on average >95%. In fact, in their study COD was mainly removed in the initial HF bed. Likewise, a full-scale hybrid CW at a resort hotel in Italy, based on a 160-m^2 HF CW and a180-m^2 VF wetland in series, achieved 95% removal of BOD_5 (Masi and Martinuzzi, 2007). Note that these comparisons should be taken with caution since configurations are not exactly the same.

The concentration of TSS in the raw wastewater was fairly high (239 ± 126 mg/L) and also larger than the one monitored in previous campaigns (around 161 ± 68 mg/L) (Ávila et al., 2013a). Their retention within the HUSB reactor was only limited, being on average of 30%, which is a value much lower than the 85% achieved during the previous operation of the plant with an Imhoff tank (Ávila et al., 2013a). In consequence, the load of TSS applied to the VF beds was fairly high (44 g m^{-2} d^{-1}), and although no evidence of clogging was observed during this study, any possible further accumulation of solids on the surface and decrease of the infiltration capacity should be carefully observed. The fact that two beds alternate their operation may have helped in the mineralization of accumulated solids during resting periods. As with the organic matter, the VF beds were able to trap the major part of these solids, achieving a removal efficiency of 83%. The overall TSS removal efficiency of the treatment plant was 96%, which is larger than the 84% reported by Masi and Martinuzzi in a hybrid CW system at full-scale (2007).

Influent concentration of NH_4-N was 28 ± 11 mg/L. As with the previous parameters, this increased 22% during its passage through the anaerobic reactor. This can be attributed to the ammonification of particulate-N through hydrolysis (Mahmoud et al., 2004; Moharram et al., 2015). The concentration of NH_4-N decreased 50% in the VF system due to its nitrification, and this was reduced further in the HF and the FWS wetlands, up to the final effluent which had a concentration of 7.2 ± 5.9 mg/L, representing a total removal efficiency of 75 ± 21%. This value is lower than that observed by Ávila et al. (2013a) when operated the plant with ¼ of the current HLR, which achieved final concentrations below 1 mg/L and removal efficiencies above 95%, presumably due to more oxygenated conditions of wetlands under smaller HLRs. Compared to other studies, this removal was also lower than the 88% removal found by Herrera-Melián et al. (2010) in an experimental hybrid wetland of similar characteristics (0.7 m^2 VF and HF wetlands in series), but similar to those reported in another experimental VF + HF system working at a HLR of 0.2 m d^{-1} in Tunisia (Abidi et al., 2009). Moreover, these efficiencies are also similar to that obtained by Öövel et al. (2007) in a full-scale schoolhouse hybrid system of similar configuration based on a VF wetland followed by a HF bed (average of 77%).

Concentrations of NO_x-N were below limit of detection in inflowing wastewater and HUSB effluent, and NO_x-N values increased during its passage through the VF beds, up to a value of 14.8 ± 7.1 mg L^{-1}, due to nitrification. This concentration was very similar to that found at nominal HLR, of 16.3 ± 3.2 mg L^{-1} (Ávila et al., 2013a). The reduction of NO_x-N was fairly low and very variable (12 ± 48%) in the HF bed, and slightly higher in the FWS wetland (34 ± 52%). These efficiencies could be improved since remaining NO_x-N was still present in the final effluent (7.7 ± 6.8 mg L^{-1}). Nevertheless, these removal efficiencies are similar to those obtained when the plant operated at the nominal HLR, whose values were 22% and 0% in the HF and FWS wetlands, respectively. The fact that a higher denitrification took place within the FWS wetland in this study could be owed to the fact that the system was more mature, and had more organic matter content provided by the accumulated plant dead material, which would make a more complex unit with a predominantly anaerobic environment. In general, the system discharged a large amount of nitrates that could be reduced by introducing a recirculation up to the VF bed or the HUSB reactor (Ayaz et al., 2015).

There was no retention of PO_4-P along the treatment system. In fact, there was an increase of orthophosphate within the HUSB reactor due to the hydrolysis of organic P, and this remained constant throughout the system (Table 2), presumably due to the maturity of the system and the low HRT given the high HLR applied. A similar tendency was observed for the concentration of sulfates, where little elimination occurred, which mostly occurred within the HUSB reactor given the anaerobic conditions (Table 2). These results are in accordance with those obtained under the nominal HLR, where only 11% and 10% removal of PO_4-P and SO_4^{2-} occurred, respectively (Ávila et al. 2013a).

In general, the hybrid treatment system has shown to be a robust treatment system capable of handling the majority of the contaminant load on a long-term basis (one year) when working at high hydraulic loading rates (four times the nominal HLR). This has been possible through the contribution of the different CW configurations, which have allowed the total specific area requirement be as low as 2 m^2/PE.

3.3. Seasonal influence

The treatment performance for various parameters as a function of the season is found in Fig. 3. TSS were not affected by a seasonal effect. While there was a high variability on inflowing concentration of TSS depending on the season, there were no differences at the effluent of VF beds, and final removal efficiencies were >95% at all seasons. On the other hand, whereas there were no clear patterns for the COD values, final BOD_5 removal efficiencies seemed to be affected by seasonality, being larger in spring (96 ± 4 %) and summer (98 ± 1%), than in fall (89 ± 2%) and winter (87 ± 5%), presumably due to the higher microbial activity under higher temperatures (Akratos and Tsihrintzis, 2007; Garfí et al., 2012). The highest value of BOD_5 removal was observed in summer (99%) and the lowest one in winter (79%). The reduction of NH_4-N was the most affected by temperature changes, showing significantly larger removal efficiencies during warmer periods, with the following values in decreasing order: 92 ± 10% in summer, 81 ± 13% in fall, 69 ± 24 % in spring and 67 ± 19% in winter. The dependence on temperature for ammonium removal is well documented (Akratos and Tsihrintzis, 2007; Antoniou et al., 1990; Cho et al., 2014; Garfí et al., 2012).

3.3. Performance of the system under the simulation of a storm event

First of all, it has to be pointed out that the first flush phenomenon and increasing OLR which usually follows a storm event was not simulated due to technical limitations. Hence, the expected concentration curve of a real storm case did not occur. This curve is characterized by a peak of the concentrations occurring a little bit after the beginning of the storm, followed by a decrease of the concentrations due to a dilution effect (Ávila et al., 2013c; Suárez and Puertas, 2005). In this case, all the water quality parameters concentration suffered a drastic decline because of the dilution with tap water. These conditions could be representative of the wet season in tropical countries, where most of the solids and organic matter contained in sewer systems may have already washed off after the first rains.

Fig. 4 shows the evolution of COD concentrations at each treatment unit during the storm event. As expected, in the stirred influent wastewater tank the COD decreased drastically because of the dilution of the raw wastewater with the incoming rainfall during the duration of the episode (hour 1) and then, after the end of the episode (hour 2), it increased up to the average values in wastewater. At the effluent of the HUSB reactor, the concentration of COD at t=0 was almost double of that found in the wastewater (i.e. 674 vs. 358 mg L^{-1} in the HUSB and wastewater tank, respectively), demonstrating the release of some of the sludge layer off the reactor immediately after the beginning of the simulation (note that during the first hour of simulation the HRT of the HUSB has been punctually decreased down to 0.75 h. This HRT returns to the normal value (i.e. 7.5 h) from the second hour onwards). Subsequently, the same dilution effect that occurred at the influent wastewater tank took place right after the release of sludge of the HUSB reactor. COD concentrations remained low (around 100 mg L^{-1}) until hour 6 when COD concentration rose again up to expected values under normal conditions. Initial COD concentrations at the VF, HF and FWS wetlands were quite similar to those found in the long-term operation of the system (95, 71 and 31 mg COD L^{-1} for the VF, HF and FWS wetlands, respectively). Although there was a minimum in COD concentration after 6 hours for the three wetland configurations, values remained similar throughout the experiment, with no particular trends observed and showing a relatively stable concentration during the whole campaign, which indicates the robustness of the system and their capability to cope with major storm events. Average final effluent COD values during the episode were slightly lower than those found in the long-term operation period (59 ± 26 mg L^{-1} and 73 ± 38 mg L^{-1} in the rainfall event and under normal conditions, respectively).

The evolution of TSS concentrations at each stage of the system under the simulated major storm episode is really similar to that of COD (Fig. 4). Firstly, TSS concentrations drastically decreased in the stirred influent tank as the heavy rainfall was simulated. As with the COD, a higher amount of solids was found at the HUSB reactor in comparison with the influent due to the initial dragging of solids from the same. While TSS values fluctuated in the wastewater tank, those remained low in the HUSB reactor (<25.7 mg L^{-1}) until hour 6. The VF, HF and FWS wetlands showed relatively constant TSS concentrations, as with the COD, being especially low in the HF and FWS units, below 6 mg L^{-1} and 2 mg L^{-1}, respectively. Average TSS values at the final effluent during this storm episode (0.8 ± 0.8 mg L^{-1}) were much lower than those registered under normal conditions (8.2 ± 6.5 mg L^{-1}).

Just as it happened for COD and TSS, a drastic drop of NH_4-N concentrations took place in the influent and HUSB just after the beginning of the storm event (drop of 23 to 2 mg L^{-1} and of 33 to 9 mg L^{-1} at the wastewater tank and the HUSB reactor, respectively). As with the other parameters, NH_4-N concentrations in the influent tank returned to usual values at hour 2. However, in the HUSB reactor values remained low up to hour 6 being below 12 mg L^{-1}. This period of low concentrations (which lasted several hours and has been observed for all examined parameters) roughly coincides with the HRT of the HUSB reactor, which would presumably be gradually releasing the diluted wastewater during that period of time. NH_4-N concentrations slightly fluctuated in the VF and HF wetlands, with no observable trends. On the other hand, the FWS wetland showed constant concentrations during the whole campaign, with values below 7 mg L^{-1}.

Overall removal efficiencies of the treatment system under this rainfall event were on average of 83%, 99% and 80% for COD, TSS and NH_4-N, respectively. Note that samples were also taken the following day to this experiment and values fell within the range of those reported under normal conditions in Table 2.

Moreover, it was also important to study the response of the HUSB reactor sludge blanket to the heavy rain episode. Despite of the increased flow, the HUSB did not seem to lose much sludge, and this happened at the beginning of the experiment when the HLR was ten times larger than usual. VSS concentrations of its effluent were measured the day before and the day after the test, resulting in 9 g/L and 7 g/l respectively, and the following week the concentration was stable again (10 g/L).

To sum up, the removal efficiencies of the treatment plant did not vary significantly from the ones obtained under normal conditions and the hybrid system showed a good efficiency during the storm experiment. The contaminants concentration seemed to return to the normal average ones for some units around 7 hours after the storm event had finished (i.e. HUSB, VF CW). On the other hand, for HF and FWS CWs fairly constant concentrations were observed. The system has proven to be robust and able to handle on heavy rain episodes, which makes it a suitable water treatment engineering solution for warm climate countries with rainy seasons.

4. Conclusions

In this study, the long-term performance, as well as the seasonality, and the impact of a major storm event of a hybrid wastewater treatment system based on an anaerobic reactor followed by three stages of constructed wetland types at experimental scale was evaluated.

Under an inflow of 800 L d^{-1} (HLR = 0.27 m d^{-1}; OLR = 103 g BOD_5 m^{-2} d^{-1}), which corresponds to 4 times the nominal hydraulic loading rate, the system achieved very high values of removal of nutrients and organic matter (82, 93, 96 and 75% for COD, BOD_5, TSS and NH_4-N, respectively). Removal of PO_4-P and SO_4^{2-} were though fairly low, of 11 and 10%, respectively. As expected, the passage of the wastewater through the HUSB reactor in general increased concentrations of BOD_5 and NH_4-N due to hydrolysis. However, the retention of TSS within the HUSB reactor was rather low (30%), showing a much poorer performance than the Imhoff tank implemented in previous phases (85%). In this sense, the use of an Imhoff tank as a primary treatment to the constructed wetlands is highly recommended due to its superior performance, simplicity and reliability of operation.

These removal efficiencies showed seasonality for some parameters, finding higher values in summer (98 and 92% for BOD_5 and NH_4-N, respectively) than in winter (87 and 67% for BOD_5 and NH_4-N, respectively). Ammonium nitrogen was the parameter which was the most affected by environmental temperature.

The experimental hydraulic retention time (HRT) of the hybrid system was observed with a tracer test. The measured HRT of the entire system was of about 38 h, which is importantly larger than the theoretical HRT of 28 h. The experimental system showed a good performance and a very good buffer capacity under extreme rainfall events. During the experiment which simulated a major storm event (which increased the HLR 10 times during 1 hour) removal efficiencies did not vary significantly from the ones obtained under normal conditions (average of 83, 99 and 80% for COD, TSS and NH_4-N removal, respectively). In such episode, firstly contaminants concentrations decreased; then they returned to average values. This was especially observable in the influent wastewater tank and the HUSB reactor effluents, while values in the CWs remained fairly constant throughout this assay. Moreover, the sludge within the HUSB could handle on the increased flow. Thus, it was proved that the system can cope with sharp fluctuations in flow to be treated.

In conclusion, the hybrid system based on anaerobic reactor followed by three constructed wetlands in series showed to be a robust technology for wastewater treatment under high HLRs and under punctual heavy rainfall, showing to be an adequate solution for wastewater treatment in small agglomerations and decentralized areas, especially in warm climate regions. The specific area requirement under the long-term operation showed to be as low as 2 m^2/PE. Note that this treatment system should be operated during a longer period of time in order to observe any possible clogging development in the wetland units.

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FIGURES

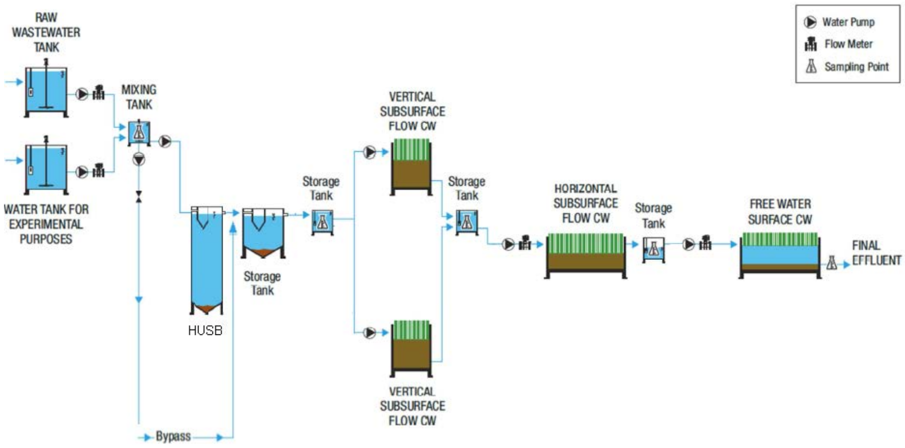

Figure 1. Diagram of the hybrid treatment system indicating pumps, flow meters and sampling points.

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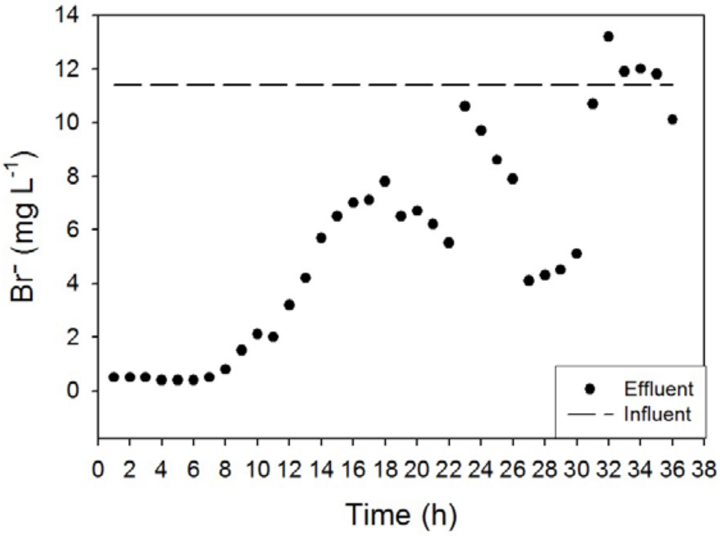

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694 Figure 2. Tracer test curve (measured at the final effluent).

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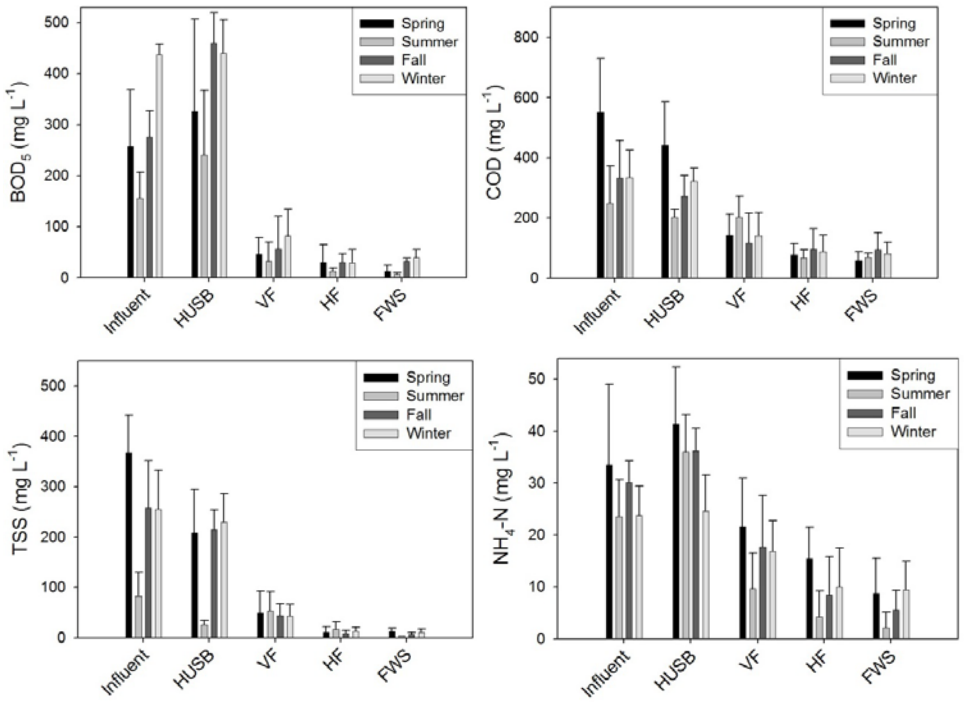

Figure 3. Average values of water quality parameters at the effluent of the different treatment units at different seasons.

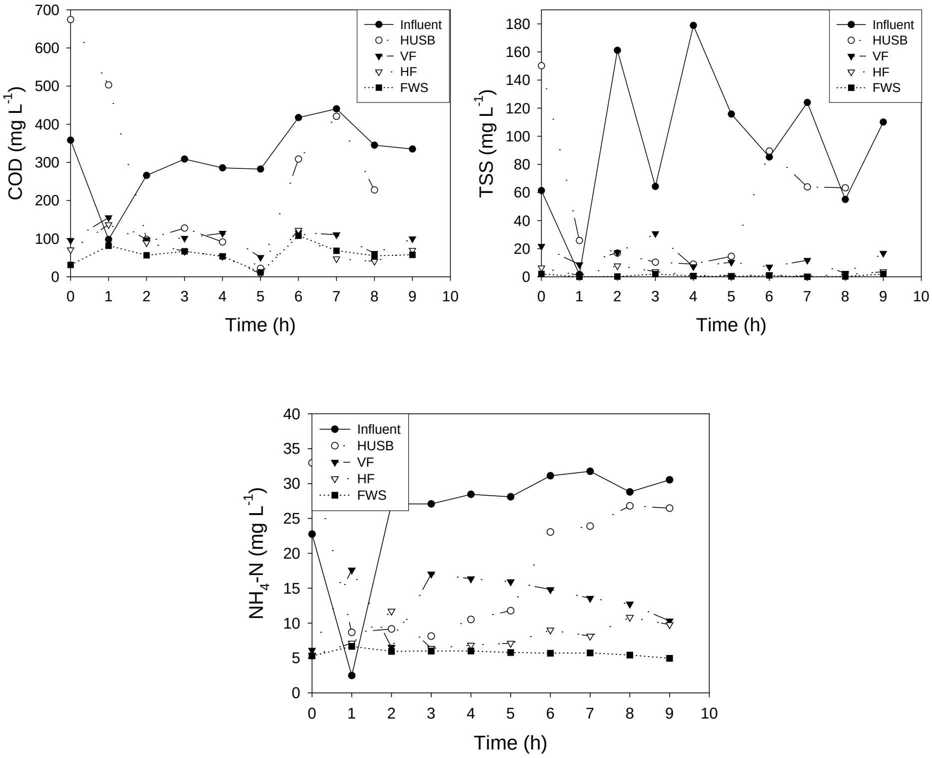

Figure 4. Evolution of the COD, TSS and NH$_4$-N concentrations at each stage of the system during the major storm event.

TABLES

Table 1. Main characteristics of the treatment system.

Parameter	Unit	Value
Average Inflow	L d^{-1}	800
Dimensions HUSB	m (internal Ø x useful height)	0.44 x 1.7
Dimensions VFs	m (W x L x D)	1.0 x 1.5 x 1.3
VF filling media	Depth of layers: m	Upper layer: 0.1 m of sand (1-2 mm)
	Grain size Ø: mm	Bottom layer: 0.7 m of fine gravel (3-8 mm)
Dimensions HF	m	1.0 x 2.0 x 0.3
HF water depth	m	0.25
HF filter media	Main media: mm	Main media: 0.3 m of gravel (4-12 mm)
	Inlet and outlet: cm	Inlet and outlet: stone (3-5 cm)
Dimensions FWS	m	1.0 x 2.0 x 0.5
FWS free water column	m	0.3
Average OLR*	g BOD_5 m^{-2} d^{-1}	103
Average HLR*	m d^{-1}	0.27

*These values were calculated taking into consideration only the area of VFs (i.e. 3 m^2).

Table 2. Average concentrations of conventional water quality parameters (± s.d.) during the period from April 2013 to May 2014 at the effluent of the different treatment units of the hybrid constructed wetland system when operating at HLR = 0.27 m d^{-1} (n=31).

	Influent	HUSB	VF	HF	FWS
pH	7.7 ± 0.4	7.4 ± 0.3	7.5 ± 0.4	7.5 ± 0.4	7.5 ± 0.4
E_H (mV)	+95.6 ± 82.7	-105 ± 36	+83 ± 41	n.a.	+105 ± 59
TSS (mg/L)	239 ± 126	166 ± 100	47 ± 31	12 ± 11	8 ± 7
BOD_5 (mg/L)	293 ± 112	388 ± 133	57 ± 48	27 ± 26	21 ± 16
COD (mg/L)	409 ± 195	335 ± 139	147 ± 78	82 ± 47	73 ± 38
NH_4-N (mg/L)	28.4 ± 10.7	34.7 ± 10.3	17.3 ± 8.8	10.7 ± 7.5	7.2 ± 5.9
NO_3-N (mg/L)	<LOD	<LOD	14.8 ± 7.1	13.0 ± 7.1	7.7 ± 6.8
NO_2-N (mg/L)	<LOD	<LOD	0.7 ± 0.5	0.3 ± 0.3	0.4 ±0.4
PO_4-P (mg/L)	2.5 ± 0.6	3.2 ± 0.9	3.2 ± 0.8	3.2 ± 0.7	3.2 ± 0.7
SO_4^{2-} (mg/L)	135 ± 23	90 ± 30	110 ± 26	113 ± 27	117 ± 22

<LOD: below limit of detection. N.a. non applicable.